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H. A. Bethe

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THE STORY OF THE LOS ALAMOS LABORATORY *

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The Los Alamos Laboratory was established as the last of the four major projects in the atomic bomb program. The purpose of the three earlier projects was to manufacture active materials which could be used in an atomic bomb. Two of them--the project of Dr. Lawrence at the University of California and of Dr. Urey at Columbia University were concerned with the separation of the active isotopes 235 from ordinary uranium using two different methods. The third, the Metallurgical Laboratory at Chicago, developed methods to produce the entirely new element plutonium by means of a nuclear reaction. All of these projects were, in the Spring of 1943, at a stage of transition from research to actual production. At this stage it seemed appropriate to establish a further laboratory to investigate the actual construction of an atomic bomb.

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This laboratory was built at Los Alamos, near Santa Fe, New Mexico. As Director, General Groves who was in over all charge of the atomic bomb project, appointed Dr. J.R. Oppenheimer, well-known theoretical physicist from the University of California. The laboratory was first intended to be quite small with a total staff of one or two hundred. It soon was found that the problems in designing an atomic bomb were much too difficult and varied to be solved by such a small staff and the laboratory soon grew to more than ten times its original size. An entire city was

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built to house the laboratory personnel at this remote locality. The city, and the laboratory especially, were closely guarded and the remote location gave added assurance of the secrecy of the development.

The laboratory was organized in several large divisions to deal with the various problems of experimental nuclear physics, theoretical physics, chemistry, metallurgy, engineering and others. At the present time, the major divisions are under the direction of R. F. Bacher, experimental physicist of Cornell University; H. A. Bethe, theoretical physicist at Cornell University; E. Fermi, physicist of Columbia University and previously a prominent member of the Chicago Metallurgical Laboratory; J. W. Kennedy, chemist from the University of California; G. B. Kistiakowsky, physical chemist of Harvard University; Captain W. S. Parsons, U.S.N.; C. S. Smith, metallurgist previously with the American Brass Company and now Professor at the University of Chicago; R. R. Wilson, physicist at Princeton University; and J. R. Zacharias, physicist from Massachusetts Institute of Technology. S. K. Allison served as a coordinator of the work of various divisions and K. T. Bainbridge was in charge of the special project to test the working of the atomic bomb. A large number of well-known physicists, chemists and metallurgists and an even greater number of younger scientists formed the staff of the laboratory.

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The following is intended to give an account of the activities of the laboratory which unfortunately must still be incomplete because some of the work cannot be released for security reasons.

When the Los Alamos Laboratory was established in the Spring of 1943, one thing was clear. A successful atomic bomb would require an extremely rapid nuclear reaction. When a nuclear reaction takes place the material is heated up by the nuclear energy released and a high pressure is produced. In fact, it is just this high pressure which makes the nuclear explosion so tremendously effective. However, this high pressure will naturally make the material, in which the fissions occur, expand and therefore become more dilute. As a consequence, the neutrons will leak out of the active material more easily instead of causing more fission. Thus, the nuclear reaction will stop when the active material has expanded to a certain amount. Therefore the nuclear reaction must be very fast in order to produce a large amount of energy before it is stopped by expansion.

If the reaction were slow, then a very small pressure would have time enough to expand the material and stop the reaction. In fact, if, for instance, one of the piles of the Chicago Metallurgical Laboratory went out of hand the resulting explosion would be much milder than that of an equal weight of an ordinary explosive like TNT.

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Therefore the atomic bomb would have to work very fast. In fact, in the actual atomic bomb as now constructed, the most important phase of the reaction takes place in a time of about 1/100,000,000 of a second. If one wants to have the nuclear reaction take place as fast as this one must use for it neutrons which are themselves fast. This is possible because the neutrons when they come out of the nuclei after fission, have a velocity of the order of 10,000 kilometres per second. One must use them while they are still as fast as this, and it will not do to slow them down to "thermal" velocities of the order of 1 kilometre per second as it is done in the pile. Therefore, one must not use large amounts of slowing down materials such as graphite but one should use essentially the active material, uranium 235 or plutonium 239, by itself.

The use of fast neutrons involves one very serious disadvantage; the chain reaction will only take place when there is a considerable amount of active material. It is true that even a small lump of active material when exposed to a neutron source will undergo fissions and thereby will make some extra neutrons; but most of these neutrons will leak out of the lump and not enough will be kept in to cause further fissions and to sustain a chain reaction. If a chain reaction is to be possible then on the average at least one of the neutrons produced in each fission must collide with a nucleus of the active material and produce another fission. The number of neutrons produced in each

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fission is between two and three; therefore not more than 1/2 to 2/3 of the neutrons produced must be allowed to leak out of the active material. If one uses a big enough lump of active material, a sufficiently large fraction of the neutrons will be kept in and a chain reaction will result. It is obviously most advantageous to use lumps of spherical shape because then the surface through which the neutrons leak out is the smallest possible for a given volume. The smallest mass of active material which will sustain a chain reaction is called a critical mass. If exactly a critical mass is assembled, just as many neutrons are lost by leakage as are produced in the active material; therefore the neutron intensity remains constant in time. If any more material is brought together, more neutrons will be produced than leak out; therefore the number of neutrons will increase more and more and in the end an explosion may result. A critical mass would exist for slow neutrons as well as for fast, but it is much larger in the case of a fast neutron reaction.

One of the prime problems of the Los Alamos Laboratory was then to get as good estimates as possible for the critical mass and also to find arrangements which would make the critical mass smaller if that was possible. One important problem in which an approximate knowledge of the critical mass was essential was the planning of production of active materials, because any production would be useless if it was not possible to produce a critical mass in a reasonable time. The only way to estimate

the critical mass was to use the measured probabilities of individual nuclear reactions and an elaborate theory of the diffusion of neutrons through the material of the bomb. On this basis it was estimated that about 15 kilograms of pure uranium 235 or 6 kilograms of plutonium would be one critical mass. On the basis of these figures production was planned and at one stage it was decided to expand considerably the production of uranium 235 in order to be sure to produce at least about one critical mass per month.

A more detailed knowledge of the value of the critical mass was required for making plans for the actual assembly of the atomic bomb. Designs had to be made of its shape and size early enough to get the complicated auxiliary machinery manufactured. Therefore the main task of the laboratory was to get as soon as possible firm estimates of the critical mass.

The difficulty in solving this problem was that at the time only minute amounts of the active materials were available. There was a gram or two of uranium 235 which had been collected in the experimental mass spectograph in Lawrence's laboratory. There was about 1/10,000 of a gram of plutonium which had been manufactured extremely laboriously by irradiating half a ton of uranium with the neutrons from a cyclotron and then separating chemically the plutonium from the immense mass of uranium. With these minute amounts of active material it was intended to find out whether the critical mass was, let us say, 10, 15, or 20 kilograms of uranium 235.

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This had to be done by measuring the properties of the atomic nuclei of these substances. Each nucleus presents to a neutron a certain target area (called effective cross-section). When a neutron is released somewhere in a mass of active material it will travel in a straight line until it hits another nucleus. The target area of the nucleus is extremely small and a solid piece of matter consists mostly of empty space, with a very small fraction of the space actually occupied by atomic nuclei. Therefore, a neutron will fly a long distance before making a successful hit. For instance, in uranium 235 a fast neutron will fly approximately 10 centimetres before it finds its target and produces a fission in a uranium nucleus. By this time it has traversed close to a billion atoms but it has gone through their empty spaces instead of hitting their small nuclei. The size of a critical mass for a fast neutron chain reaction is determined just by the consideration that the diameter of the active material must be at least of the order of the distance of flight of a neutron from one fission to the next—that is, about 10 centimetres. Also the time in which the nuclear explosion will take place follows from the same argument: at a velocity of 10,000 kilometres per second a distance of 10 centimetres is traveled in 1/100,000.000 of a second.

Slow neutrons can react with a nucleus much more easily; a travel of about 1/3 millimetre is enough for a slow neutron to find a uranium 235 nucleus in which to make fission. This is the

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reason why the critical mass would be much less for a slow neutron chain reaction than for a fast neutron reaction. It should not be believed, however, that a uranium 235 piece of 1/3 millimetre diameter would sustain a slow neutron chain reaction--but that is a later story.

To return to the problems of measurement, it was necessary to find accurate values for the effective cross-sections of the active nuclei for neutrons. These cross-sections vary with the velocity of the neutron; therefore measurements had to be made for neutrons of all possible velocities. Likewise the velocities of the neutrons coming out of the fission had to be measured. Moreover, until the Los Alamos Laboratory was established, experiments had been done only with <u>slow</u> neutrons causing fission. It was known that in this case neutrons were emitted as a consequence of the fission. There was strong reason to believe that this would also be true if the fission were caused by fast neutrons as it would be in the atomic bomb. But nobody had seen this happen yet and there was at least the possibility that no neutrons, or not a sufficient number of them, would be emitted in a "fast fission", i.e., a fission caused by a fast neutron. If this had been the case the atomic bomb project would have ended right then and there. Actually, one of the first results of the Los Alamos Laboratory was that at least as many neutrons were emitted in fast fission as in slow fission, and later experiments showed that there were actually slightly more. And the new element, plutonium, was found to be superior to the previously investigated

uranium 235 in the number of neutrons emitted in each fission as well as in the cross-section it offered to fast neutrons. Hence, the much smaller critical mass for plutonium mentioned above. This was most welcome, especially because in the long run, quantity production of plutonium seemed somewhat cheaper than of uranium 235 provided it worked at all.

There was still another doubt in the minds of the physicists at Los Alamos. This doubt concerned the time it would take after a fission for the neutrons to be emitted. It was not a strong doubt because reasonable theoretical estimates put this time at about 1/100,000,000,000 of a second or less. This time is exceedingly small even compared to the time of flight of a neutron from one fission to the next which we saw was 1/100,000,000 of a second. But there were some features in the velocity distribution of the neutrons emitted in fission which nobody understood and one possible (though not likely) explanation was that it might take a longer time for the neutrons to be emitted. If this had been true, it would have again made the construction of an atomic bomb impossible because the nuclear reaction would have taken a longer time than was expected and therefore the active material would have been used very inefficiently.

One of the first experiments done by the Los Alamos Laboratory was, therefore, the measurement of the time elapsing between a fission and the emission of the neutrons. This was quite difficult because the times of interest were of the order

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of 1/100,000,000 of a second or less. No neutron detector would be able to measure such short times, and even the modern development of electronic equipment makes it only just possible to record such times at all. The problem was solved in a rather ingenious way by using the fact that immediately after the fission, the fission fragments will travel away with very high velocities. Now the neutrons must be emitted either when the original nucleus breakes up—and in this case the time between fission and neutron emission would be zero—or else they are emitted by the fission fragments in flight. After 1/100,000,000 of a second these fragments will be about 10 centimetres from the point where the fission took place if there is no material around to slow them down. On the other hand, they can be stopped by thin foils of metal or even by a centimetre or two of air. The measurement then was designed to find out where the neutrons were emitted rather than when. A foil of uranium 235 was wrapped around a neutron counter and the fission fragments permitted to travel into an evacuated space. If the neutrons were emitted after 1/100,000,000 of a second or more, most of them would be emitted very far from the neutron counter and therefore only a small fraction of them would be counted by the neutron counter. On the other hand, if they were emitted much more quickly, practically all of the neutrons would reach the counter. To make a quantitative comparison, a second experiment was made in which the foil of 235 was covered by another metal foil thick enough to

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stop all fission fragments. In this case, no matter when the neutrons were emitted, they would all be emitted close to the counter. The two experiments gave exactly the same neutron count and it was therefore concluded that within the accuracy of the measurement all neutrons were emitted at times much less than 1/100,000,000 of a second after the fission.

When these two principal doubts about the workability of the atomic bomb were removed, one of the main questions was what could be done to reduce the required amount of material. If one used the active material just by itself something like 40 kilograms of uranium 235 would be required for one single critical mass. Something like 100 kilograms would probably be necessary to make an efficient atomic bomb. However, we know that the existence of a critical mass is caused by the leakage of neutrons out of the active material. It was clear then that one should provide a "container" to keep the neutrons in. Now, any atomic nucleus has the property of scattering neutrons; therefore, if the active material were surrounded by any substance at all the neutrons leaking out would at least in part be reflected back into the active material and would thus have a chance of causing more fissions. Therefore, a neutron reflector, a "tamper", was an essential part of the atomic bomb.

The question was what substance to use for the tamper. It was obviously an advantage to use a material which had a large number of nuclei in a given volume because then the reflection

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of neutrons would be more likely. Moreover, each nucleus should have a large effective cross-section for scattering the neutrons. Most nuclei can also capture neutrons; this is obviously an undesirable property and the probability for capture should be low. Finally, it was desirable that the neutrons should not be slowed down too much by the scattering in the tamper; therefore measurements were made not only of the probability of scattering but also of the velocity of the neutrons after they had been scattered.

Quite a number of elements seemed good possibilities from the start. With regard to the first property required almost all the heavy elements qualified, e.g., ordinary uranium, gold, tungsten, platinum and others. But also some of the light elements have a high number of nuclei per unit volume and have sufficiently great cross-sections to be good neutron reflectors. As a matter of fact, beryllium seems to be the best neutron reflector so far discovered and also graphite is satisfactory. In addition to the elements, compounds had to be considered: for instance, tungsten carbide contains almost as many tungsten nuclei in a cubic centimetre as does tungsten metal itself, and the scattering of the carbon nuclei is obtained almost gratis.

An extensive program was therefore set up to find out what almost any conceivable nucleus would do to neutrons of almost any conceivable velocity. Some very rare substances were procured in small quantities on the chance of making good tampers

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and of being, at the same time, much cheaper than the active material; so, for instance, a pound of rhenium was at one time obtained and its properties measured. Since it did not seem to have any special virtues it was abandoned, and the same happened to other rare elements such as platinum and iridium. Gold should not be considered as a particularly rare metal in this connection because amounts of, say, 1000 lbs. are readily available, and even the expense of such amounts of gold would be only a few percent of the expense of producing the active material. However, gold was found to capture neutrons very strongly and was therefore undesirable.

The very light elements were rejected on another ground. In addition to reflecting neutrons the tamper also has the desirable property of offering mechanical resistance by its inertia to any expansion of the active material. It will therefore keep the nuclear reaction going for a longer time and permit more energy to be developed. This mechanical property of the tamper depends, of course, on its density (specific weight) and puts a large premium on the use of a heavy tamper.

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The largest pieces of carbide ever produced

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were made for this, weights up to 300 lbs. Uranium has one additional drawback which we shall discuss later on. [redacted] DOE (b)(

While this search for the best tamper was going on, another part of the laboratory was considering the design of the actual atomic bomb. If one assembles more than one critical mas of active material an explosive nuclear reaction will occur as soon as there is a neutron to set it off. As long as all neutrons are kept away from the active material there can be no fission and no multiplication of neutrons. Neutrons, however, are everywhere. There are some neutrons in cosmic rays and this source alone would start a nuclear chain reaction in about a second. Other sources of neutrons are more powerful. One of the most important is due to the fact that the materials which undergo fission are also radioactive and spontaneously emit alpha particles. These alpha particles, in turn may cause nuclear reactions with other nuclei. Many of these reactions lead to the emission of neutrons. The reactions are very improbable with heavy nuclei, but highly probable with some light nuclei especially lithium, beryllium and boron, but also to a smaller extent with such common elements as carbon and oxygen. It is impossible to keep the active material entirely free from impurities such as these. Therefore, there will necessarily be some neutrons produced in the material, and if more than one

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critical mass is assembled for more than a certain very short time, a nuclear explosion will result.

These considerations show the necessity of two things: First, to bring the material together in a very short time. Second, to purify the active material very carefully from all light elements which might give neutrons when bombarded by alpha particles.

The latter problem was a most difficult one for the Chemistry and Metallurgy Division of the laboratory. The tolerance of some of the light elements was fantastically small, especially if plutonium was used for the active material because this substance emits a very large number of alpha particles. Not more than one part of beryllium in 10 million parts of plutonium could be tolerated even if it were the only impurity producing neutrons. Special methods had first to be devised to detect such exceedingly small percentages of beryllium and other light elements. This problem was successfully solved by a combination of spectroscopic and chemical methods.

In every case, this development of analytical methods was made more difficult by the extreme value of the plutonium, which required that only very small samples be taken for analysis. For most impurities, only a few milligrams were needed for the analytical techniques eventually developed. For example, usual analytical procedures for oxygen in metals ordinarily require samples of about one gram, lack the sensitivity required for

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this case, and frequently are not applicable to an element as electropositive as plutonium. In this laboratory a method was developed in which a sample of twenty milligrams of plutonium metal was heated to 2000° C in graphite, in a very good vacuum so that the gases evolved could be analyzed for carbon monoxide and carbon dioxide to a sensitivity of five parts of oxygen per million parts of plutonium. The spectrographic group used procedures of even greater sensitivity for most metallic element impurities.

An even greater problem was then actually to achieve the exceedingly high purity of the active material. Very effective purification procedures were eventually worked out, and they required special chemical reactions and reagents, much platinum and quartz apparatus and even air-conditioned laboratories. But during the period when these procedures were under investigation and development, there was comparatively very little plutonium with which to work. When this chemsitry laboratory was established in early 1943, it brought here from Berkeley about 100 micrograms (1 microgram = 1/1,000,000 of a gram) of this entirely new element which had been laboriously, and wonderfully, isolated from 500 lbs. of uranium nitrate irradiated for over a month by neutrons from the cyclotron. This work had revealed some fundamental chemical properties of element number 94 (named plutonium for more reasons than one), but further long and difficult studies were necessary and were carried out in cooperation with other

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project laboratories. For almost a year, the chemical reactions, oxidations and reductions, solubilities of compounds, formation of complex ions, of these 100 micrograms of plutonium (eventually supplemented by an additional cyclotron preparation) were studied under the objectives of compound microscopes. To achieve the necessary economy of material, one program of measurements was undertaken with only one-tenth of one microgram, and visual physical-chemical measurements were made on as little as one one-hundredth of a microgram.

Plutonium proved to be a very interesting element chemically. The work here closely paralleled studies at the University of California and the Metallurgical Laboratory in Chicago, in revealing the nature of its chemical behavior. Plutonium is now one of the better known elements in this regard. It rather readily exists in water solutions in oxidation states +3, +4, +5, and +6; the +4 and +6 states show strong chemical resemblances to corresponding states of uranium.

In time, as much larger quantities of plutonium became available from project plants, a new difficulty became very important and to a large extent determined the nature of final chemical and metallurgical operational techniques. Since the new substance is not much less radioactive than radium it is an extremely toxic material, and amounts of it large compared to the world's supply of radium had to be extensively processed. Project medical groups estimated that a man could tolerate no more

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than five micrograms in his body. In ordinary processing of kilograms, the spreading of dangerous amounts over the entire laboratory would be inevitable. This difficulty was overcome by operating mostly from the outside of sealed systems, by the use of special personnel protective measures, and by the maintenance of laboratories as uncontaminated as possible through the use of many special monitoring instruments developed by project instrument sections and capable of detecting quickly as little as 1/300,000,000 of one gram of plutonium.

Even if infinite chemical purity could be achieved there would remain still another source of neutrons which necessitates rapid assembly. All nuclei which can be made to undergo fission by neutron bombardment can also undergo fission spontaneously without any external provocation. For most of the known nuclei the rate of this spontaneous fission is exceedingly slow—much slower than the rate at which they emit alpha particles. However, in many of them it is sufficient so that the neutrons emitted with the spontaneous fission in several kilograms of material are quite numerous. One of the nuclei which undergoes spontaneous fission at a rather high rate is the common isotope uranium 238 which emits 15 neutrons per kilogram per second. This is the reason, indicated above, why uranium is in general not suitable as a tamper. It also affects the use of uranium 235 as active material because none of the methods used to produce 235 separates it completely from 238 and therefore some

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spontaneous fission will always remain in the active material. With uranium 235 containing 20% of Uranium 238 and small amounts of impurities of light elements, about 200 neutrons are emitted per second by the material in one bomb.

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Until the bomb is to be actually used the material must be in lumps each of which must be smaller than one critical mass. Then, over the target and when the explosion is desired, two or more such lumps must be thrown together to form one big mass and this must take place in a very short time. The mass finally assembled in this way should be as great as possible because then the leakage of neutrons is minimized and the nuclear reaction proceeds as quickly as possible, with a consequent increase in the available energy transformed into mechanical energy. When assembled the material should be as nearly as possible in a spherical shape and should be surrounded by a good tamper. Before assembly this is not necessary; in fact, it is an advantage to have the material then in an unfavorable shape and without much tamper because then a larger amount of material can be stored without a nuclear chain reaction taking place.

The assembly itself has to be as quick as possible. Otherwise, there is still the danger of a neutron coming along by chance and starting the chain reaction before the assembly is completed. If this happens, the configuration of the material

will be unfavorable, the neutron leakage will be greater and the efficiency of the bomb smaller.

From the beginning of the project it was considered most promising to shoot the active material together. Before the release of the atomic bomb over its target, it was planned to put about one-half of the material into a suitable tamper, while the other half was to be put as a projectile inside a gun near to, but separated from, the first half. The two halves were designed to fit smoothly into each other and to form a nearly spherical ball after assembly. The gun was then to be fired at the appropriate moment; it would shoot the projectile into the prepared "target" consisting of tamper and of the other half of active material, and thus make a super-critical mass. This seemed a rather fantastic scheme since the only plausible way of delivering the atomic bomb to enemy territory seemed to be by airplane.

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a matter of fact, the gun finally constructed has a diameter of over and an ordinary gun is a very bulky piece of equipment which one would not ordinarily think of carrying inside an airplane and even less of dropping inside a bomb. Added to this must be the requirement of firing this gun completely automatically and of insuring an unusually high probability of

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functioning in battle conditions. All this involved complicated electrical equipment and considerable additional weight. Furthermore, the tamper, in order to be effective, must have a large weight by itself.

This problem would have seemed insoluble with ordinary ordnance equipment. Fortunately, there was one thing that this gun was not required to do: it did not need to fire more than once. Much of the bulk of standard guns is due to the requirement that they be able to fire very many times without appreciably changing their calibre and without losing their accuracy of aim. Also, in the latter respect the atomic gun did not need to meet strict requirements since the target was to be very close to the gun itself and in fact was attached to it.

For this reason, an entirely new design could be made and was made, and the weight of the gun was reduced to less than 1/5 of the weight of standard guns of that calibre. At the same time, the length of the gun was reduced by using gun powder which would develop especially high pressures. This reduction in length was necessary in order to fit the gun and the bomb into the bomb bay of existing planes.

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The experiments were helped greatly by the fact that ordinary uranium has exactly the same mechanical properties as uranium 235 so that all experiments could be done with ordinary uranium.

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The problem of the assembly of the active material by means of a gun was therefore solved in an all-around satisfactory way. Other methods of assembly were also considered and worked upon. Some of these cannot be disclosed now for reasons of security.

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In spite of much thought given to this problem no satisfactory solution was found.

A major problem of the Los Alamos Laboratory was the fabrication of the active material in metallic form. In the case of uranium 235, it was at least known beforehand from work with ordinary uranium how to produce the metal, and the main problem was to satisfy the high purity requirements mentioned above. Plutonium, on the other hand, was a completely new element which did not exist in nature. Its metallurgical properties were

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completely unknown when the laboratory was established. Moreover, there was no hope of getting appreciable quantities of the material until about a year after the opening of the laboratory, and less than a year after that it was required to have the methods of preparation and fabrication completely worked out. It was furthermore expected that plutonium would be quite a difficult metal, metallurgically, and this expectation proved more than true.

Chemically plutonium was known to be somewhat similar to uranium and so it was natural to use uranium as a stand-in for the investigation of metallurgical processes as long as no plutonium was available. Even with the small amounts available of less than a milligram of plutonium, attempts were made to determine some of its properties, particularly its density. This was important because the critical mass would be much lower if the density were higher, because the neutrons are then more likely to find a target nucleus in which to make fission. The density determinations gave varying results between about 16 and 20 and it was not until much later that this variation was explained.

As soon as a few grams of plutonium were available, which was early in 1944, metallurgical research was begun on this substance. It was found to behave quite differently from uranium but after some unsuccessful attempts, a good method was found to obtain the metal from its fluoride. After this was accomplished,

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the properties of the metal itself were investigated, especially its behavior with increasing temperature.

It was found that this newly created element behaves in a most spectacular way. Many metals are known to exist in various modifications of different crystal structure, changing over from one to the other at certain temperatures. Manganese has the largest number of modifications of any previously known element, namely three. They differ by a few percent in density and usually somewhat more in elastic and electric properties. Plutonium, on the other hand, has no less than five different modifications and changes over from one to the next about every 100° C increase in temperature. There is an extremely great difference between the densities; one modification, the "delta phase" has a density of 15.8 grams per cubic centimetre, while the "alpha phase", which is stable at room temperature, has as much as 19.8. Such a great difference in density is known in only one other element--tin--and the propensity of the metal to change its volume by a large fraction, to say nothing of other property changes that occur as frequently as the temperature is varied, makes the fabrication of this metal a particularly difficult problem. The form stable at room temperature is brittle and cannot be shaped by plastic deformation; fortunately, however, all high temperature modifications are plastic.

Plutonium has other unusual properties. In some respects it barely deserves to be called a metal. It possesses an electrical

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resistivity at room temperatures one and a half times that of bismuth, its nearest competitor among the elements, and the resistance of all phases but delta decreases with increasing temperature. Even delta is not normal, for it contracts on heating in a manner absolutely unprecedented.

An added difficulty in the manufacture was the fact the plutonium is extremely toxic because of its alpha radioactivity. Altogether plutonium is about the most disagreeable metal with which a metallurgist could be asked to fabricate special shapes on a limited time schedule, though from a scientific standpoint it is unquestionably the most fascinating.

The metal is highly electropositive, and corrodes to a loose oxide when exposed to the atmosphere. The protection of finished pieces was therefore imperative, for the dual purpose of preserving the finished surface and preventing the highly toxic oxide from being spread around the laboratory. Electrodeposited coatings were found to be undependable.

Let us return, now, to the problem of finding the critical mass. It was all very well to predict the critical mass on the basis of measurements of the properties of the nuclei with the

help of a fairly complicated theory. But this method was necessarily inaccurate and a direct determination of the critical mass was most essential, a determination made by actual assembly of one critical mass and by obtaining an actual chain reaction with fast neutrons.

A large part of the effort of the laboratory, therefore, went into preparing to handle a fast neutron chain reaction in a safe manner. It was felt that several steps on the way to this goal were desirable, both to check the existing ideas about critical masses and to give the physicists experience in controlling chain reactions. The controlling factor was the rate of production of active material which would rise very slowly at first and then very rapidly. It was, therefore, important to obtain a chain reaction with the minimum possible material. This made it necessary to rely on a slow neutron reaction.

A slow neutron reaction is by no means as directly obtainable as a fast reaction. The neutrons emerge from the nuclei at high speed; therefore in order to produce slow neutrons they have to be decelerated in a suitable medium. The most effective means of decelerating neutrons is to let them make collisions with hydrogen nuclei. The simplest way of achieving this is to use a solution of the active material in water. This solution should be surrounded by a good neutron reflector, which at the same time does not absorb appreciably the slow neutrons which one is intending to use. The best tamper for this purpose would

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probably be metallic beryllium, but since sufficient quantities of this material were not available, beryllium oxide was used which is a very good second choice to beryllium. Many technological problems had to be overcome in producing a meter cube of high density beryllium bricks, some intricately shaped. This assembly, which was known in the laboratory as the "water boiler", had to be designed as effectively as possible. The volume of the water solution must be large enough to permit fast neutrons to be effectively slowed down; the most favorable volume turned out to be about 15 litres. Since this rather large volume is required for slowing down the neutrons, there is considerable capture of the slowed neutrons by hydrogen nuclei; therefore the mass of active material must also be appreciable because it is necessary that most of the slow neutrons ~~must~~ be captured by the nuclei of the active material rather than the hydrogen nuclei. It was calculated that about 580 grams of uranium 235 would be critical if the concentration of 235 in the uranium was 14% which was the actual concentration delivered by the electromagnetic separation project at the time.

The water boiler was actually built and operated as soon as the necessary amount of 235 was available. This was the first chain reaction ever to be produced with enriched material and also the first with small amounts of material. The critical mass was found to be 580 grams. The exact agreement with the theoretical prediction was certainly fortuitous, but it was most

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gratifying that the experimental value was about the same as the theoretical and it showed that no essential point had been overlooked in the theory.

The water boiler was subsequently developed so that it could be operated at a power up to 3 kilowatts and in this modification it was most useful as a strong and easily controllable source of neutrons for experimentation.

As the next step, it was decided to reduce gradually the amount of hydrogen in comparison with the amount of uranium 235. In this way, the critical mass would increase gradually and the nuclear reaction would be carried to an increasing extent by fast rather than by slow neutrons. To carry out this program it was helpful that there existed a compound between uranium and hydrogen, UH_3, which has a relatively high density. In order to get greater hydrogen concentration, the hydride UH_3 was mixed with hydrocarbon plastic of formula approximating CH_2. In this way, mixtures containing from 60 to 10 grams of hydrogen per uranium 235 were obtained and critical masses between 3 and 10 kilograms were found.

When this hydride program was first started, it was suggested that hydride might perhaps be a more efficient way of using the active material than metal. The reason for this supposition was that collisions with hydrogen would prevent the neutrons from escaping from the active material and would thereby reduce the critical mass. It was realized, of course,

that by the same collisions the neutrons would be slowed down and there was the danger that thereby the time of flight between two fissions would be lengthened and the efficiency of the atomic bomb accordingly decreased. However, there was some hope that this might not be so. Some experiments had shown that at least in the velocity region between 5000 and 10,000 kilometres per second the time of flight between fissions appeared to be nearly constant, namely 1/80,000,000 of a second. On the other hand the time of flight for slow ("thermal") neutrons was about ten times longer. The question was, therefore, at what velocity this change of the time of flight took place, and there was at least some hope that it might take place at a velocity only slightly above the thermal. That hope was theoretically fairly well founded by the observations that the cross-sections of many other nuclei for neutrons show very violent fluctuations (resonances) at low velocities.

An extensive experimental program was therefore started to investigate the behavior of the cross-section for fission as a function of neutron velocity. It was found that as the neutron velocity was raised above thermal, the time of flight became indeed appreciably shorter, and stayed shorter upon further increase of the velocity. However, the factor by which it was shortened was only 3 instead of the expected 10. It finally turned out that the original experiments showing constant time of flight between 5000 and 10,000 kilometres per second had been

incorrect and that there was actually a gradual decrease of the time of flight with increasing velocity. This result showed that the uranium hydride would involve a considerably longer nuclear reaction time than the metal, and would therefore lead to a less efficient use of the active material even though it made the critical mass smaller.

When the critical mass for the various hydride compositions had been determined, they were used for an additional experiment which came as close as was safe to an explosive nuclear reaction. Slightly more than a critical mass of hydride was divided into a major part which was kept fixed in a tamper and a small plug which fitted into a hole of the major part and could be dropped through it along guide rails. Then for a very short time while the plug was dropping through, the assembly would be supercritical. During this time, then, the neutrons would multiply and one would obtain a large burst of neutrons whose total size and distribution in time could be calculated as well as measured. As the plug dropped out of the tamper the assembly would again become subcritical and the neutrons would decay in a very short time. This experiment of "tickling the dragon's tail" can be performed with the hydride with its relatively slow reaction time while it would be quite dangerous with metal. It was actually performed and gave both a very valuable neutron source for experimentation as well as very satisfactory agreement between the calculated and observed shape and size of the neutron pulse.

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In early 1945, after these experiments were carried out with hydride, there was enough material available to begin experimentation with 235 metal. To start with, spheres of the metal were made which were certain to be smaller than the critical mass. With each sphere, measurements were made of the multiplication of the number of neutrons coming out from a source inserted at the center of the sphere. This multiplication, which is due to the fissions and neutrons produced in the sphere, could be calculated on the basis of the previously measured cross-sections of the nuclei. The observed multiplication agreed within experimental error with the calculated one and it could, therefore, be confidently expected that the prediction of the critical mass was also correct. As the size of the metal spheres increased, more and more accurate predictions of the critical mass were possible and the final result checked with expectation almost precisely.

The first critical mass of uranium 235 metal was assembled in April 1945. This gave the first nuclear chain reaction relying entirely on fast neutrons. It proved quite easy to control. To give further checks on the theory, measurements were made of the distribution of the neutrons both in space and velocity. A measurement was also made of the time in which the neutron number would decay if the mass of active material was slightly reduced from critical. From this decay time, conclusions could be drawn about the time of flight of the neutrons

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and therefore about the probable efficiency of a bomb containing a certain number of critical masses. Similar measurements were made about two months later with the first critical assembly of plutonium. Here again the predicted value of the critical mass turned out to be correct within a few percent.

As the critical mass could be determined experimentally the emphasis of the theoretical work shifted to the prediction of the efficiency of the bomb—a problem which naturally had received much attention since the beginning of the project. The most important factor in predicting the efficiency was the rate of multiplication of the neutrons, i.e., the time in which the neutron number is doubled. This time is very long if the mass is only slightly greater than critical and decreases continuously with increasing mass of material.

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This required a long theoretical extrapolation which gave the result that approximately of a second would be required for doubling of the neutron number.

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What are the processes which will go on in an explosive nuclear reaction? When a neutron is introduced, it will make a fission which will lead to the emission of two or three neutrons. Each of these may again have a chance of producing a fission after their normal time of flight. This multiplication will go on until the number of neutrons has reached something like 100,000 billion billions. Each of the fissions which has occurred has led to the production of some known amount of energy, or rather to the conversion of this amount of nuclear energy into mechanical, or heat, energy. The active material has therefore been heated up to a very high temperature and a high pressure is necessarily connected with the high temperature. The temperature is high enough so that no only has the material been evaporated, but the atoms of the material have been stripped of most of their electrons which now run around freely in the active material. In contrast to some recent statements in the press, this process consumes large amounts of energy rather than setting energy free. When the large number of neutrons mentioned above has been produced, the pressure becomes sufficient so that the active material pushes the tamper out with a great acceleration. The acceleration is great enough so that even in a time as short as of a second the tamper acquires a large velocity and is displaced outward by a considerable amount. Therefore when the number of neutrons has again doubled, the active material has been appreciably diluted and it is therefore less likely for a neutron to find a nucleus to make fission with. This decreases the rate of multiplication of the neutrons so that the next time it may take twice as long for the number of neutrons to double. At

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the same time, the pressure has further increased so that the tamper will now move outwards with increased speed. It is clear that not long after this the active material will be so dilute that it ceases to be critical and from then on the number of neutrons is actually decreasing rather than increasing. The neutrons which are actually present will, of course, still produce some fission and some additional energy, but after another short time most of the neutrons will have been absorbed and the nuclear reaction will stop.

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Although this is not a very high efficiency it still corresponds to a very large energy release which is equivalent to the energy release from 15,000 tons of TNT. If still greater energy releases are wanted, the amount of the active material has to be increased which presents a more difficult problem of assembly but is probably feasible to a certain extent.

The project was now ready for the next to the last step: To make an actual test of a nuclear explosion. Because of the extreme costliness of the materials involved it was obvious that only one test could be made. This test therefore <u>had</u> to work and as much information as feasible had to be obtained from it. For the purpose of the test a desert site about 250 miles south of Los Alamos was selected and a large fraction of the laboratory staff was organized in a special project under the direction of K. T. Bainbridge of Harvard University,

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in order to prepare the test and the connected measurements.

For the test, the atomic bomb was not dropped from an airplane but set up on a 100 ft. tower in order to facilitate measurements. The most extensive measurements were naturally made of the blast produced by the atomic bomb because the blast is the principal way in which the atomic bomb is expected to cause damage to the enemy. About a half dozen different methods were set up and calibrated for the measurement of the blast. There were simple barographs to measure the pressure at large distances, 6 to 50 miles away. There were rugged crusher gauges to measure extremely high pressures of many atmospheres in the immediate vicinity of the atomic bomb. There were standard pressure gauges in the form of piezoelectric crystals such as are used by other laboratories and proving grounds to measure the pressure in the blast wave of bombs. There were two types of gauges based on the motion of fluid under the influence of the blast pressure. There were electric condenser gauges to measure relatively low pressures. There were more than 50 wooden boxes with holes of various sizes in them and aluminum foils stretched over the holes. A certain, relatively low pressure would burst the foil over the largest hole, a somewhat higher pressure would destroy the second largest foil and so on. These simple devices worked very satisfactorily. Perhaps the most accurate results were obtained by measuring the velocity of the blast wave at various distances from the bomb; this velocity is greater than sound velocity and from the difference one can calculate the pressure existing in the blast at the given place.

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But the atomic bomb not only produces blast, but also specific nuclear effects. It emits neutrons and gamma rays and both of these were measured at various distances from the bomb. Of the neutrons, even a "moving picture" was obtained showing the number of neutrons reaching the detector at various times. In addition, the fission produces fission fragments which are radioactive, and whose radio activity can be measured after the explosion is over. This measurement gives one of the most accurate means to determine the efficiency of transformation of active material by the nuclear reaction.

Elaborate arrangements were made to photograph the explosion in its various stages. Some cameras gave colored motion pictures. Some gave black and white pictures at ordinary speeds. Others were used at exceedingly high speeds up to 8000 frames per second in order to catch the very beginning of the blast wave in air. Moreover, there were several spectrographs to observe the color and spectrum of the light emitted by the ball of fire in the center of the blast.

Many of the members of the laboratory were engaged in the preparation of this test. Those senior staff members who were not, could see the explosion from a hill 20 miles distant. Before the test, the entire laboratory staff was anxious about the success of the test. It was true that all reasonable investigations to insure success had been made, short of a trial explosion. But then, this nuclear explosion was something so entirely new, and the construction of the atomic bomb was so entirely dependent on dead reckoning that

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it was natural for the scientists to feel some doubts whether it would really work. Had everything been done right? Was even the principle right? Was there any slip in a minor point which had been overlooked? As the members of the laboratory waited for the test they were undecided whether to expect success or failure.

The test was to take place at 4:00 a.m. provided the weather was favorable. Around midnight, it rained in torrents and there was a violent thunderstorm. To the scientists on "Observation Hill" it was not at all clear whether the test would be made. Efforts to get into radio communication with test headquarters failed. At last, there came word that the test had been postponed until after five o'clock. But it was good news that it would be made that morning. Soon enough the radio began to function. S. K. Allison of Chicago University announced the time until the shot: "Minus 20 minutes", "Minus 15" and so it went on to "minus 10 seconds".

Zero time came. Everybody had his dark glasses in front of his eyes and still the brilliance of the flash exceeded all expectations. It looked like a giant magnesium flare which however kept on for what seemed a whole minute and was actually one or two seconds. Many, who afterwards saw the sun rise through the same glasses, were convinced that the sun was nothing compared with this flash. The white ball grew and after a few seconds became clouded with the dust whipped up by the explosion from the ground. The whirling ball of fire slowly detached itself from the ground and rose and left behind a black trail of dust particles. The rise, though it seemed slow, took place at a

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velocity of 120 meters per second. After more than half a minute the flame died down and the ball which had been a brilliant white became a dull purple. It continued to rise and spread at the same time, and finally broke through and rose above the clouds which were 15,000 feet above ground. It could be distinguished from the clouds by its color and could be followed to a height of 40,000 feet above ground. The wind blowing in different directions at different altitudes made the cloud into a "Z" shape and finally blew it away to the northeast.

It was clear to everybody that the test had been a success. When the many measurements were evaluated it turned out that the energy release was close to what had been expected on purely theoretical grounds. In fact, it was slightly more. Also as expected theoretically the energy released was transformed into blast slightly less efficiently than in a TNT explosion so that the blast was the equivalent of that from 10,000 tons of TNT.

What had been accomplished? For the first time, an atomic bomb had been made and had been successful. But, at the same time this was the greatest explosion in history. The largest explosion which had ever occurred before was that at Oppau in 1923 in which 6000 tons of ammonium nitrate exploded, equivalent to about 5000 tons of TNT. The famous explosion at Halifax was only about 3000 tons of TNT, and as far as the author of this is aware, the largest amount of explosive set off deliberately before was 100 tons of TNT which were exploded by the Los Alamos project two months before the actual test

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in order to test the measuring equipment to be used.

The conditions that must have prevailed in the active material during the nuclear explosion were fantastic. The temperature was probably near 100,000,000°, four times the temperature at the center of the sun and over ten thousand times that at the sun's surface. The pressure was over 100 billion atmospheres, again more than at the center of the sun. All this was achieved by the release of some nuclear energy which made the active material about 1 gram lighter than it had been before--but there was certainly nobody about who could have measured this decrease in weight. The radioactivity of the fission products that were formed was, at one hour after the explosion, equivalent to that of a million kilograms of radium. (The total world's supply of radium is about 1 kilogram.) The effect of this tremendous radioactive radiation was plainly visible as a blue glow surrounding the cloud which was rising after the explosion. For the first 1/10 of a second, light was emitted at the rate of more than ten billion kilowatts which is far more than the electric power produced in the world. In fact, the light intensity was great enough so that it is conceivable that the explosion might have been seen from another planet.

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